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**AFRRI**  
**TECHNICAL**  
**NOTE**

**DOSIMETRY FOR  
NEUTRON RADIATION STUDIES  
IN MINIATURE PIGS**

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**ARMED FORCES RADIobiology RESEARCH INSTITUTE**  
**Defense Atomic Support Agency**  
**Bethesda, Maryland**

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DOSIMETRY FOR NEUTRON RADIATION STUDIES  
IN MINIATURE PIGS

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## ABSTRACT

Miniature pig cadavers were instrumented and irradiated in a neutron field (incident neutron to gamma kerma ratio of 5-10) and a gamma ray field (incident gamma to neutron kerma ratio of 10-15) from the AFRR-TRIGA reactor. Characterization of the radiation field included free-in-air measurements of the neutron and gamma ray components employing the paired chamber concept. Depth-dose patterns across the brain and intestinal regions were measured for each of the radiation fields employing a miniature tissue-equivalent ionization chamber.

## I. INTRODUCTION

The Armed Forces Radiobiology Research Institute is conducting a series of biological irradiations to determine the effectiveness of reactor-produced radiations for intestinal damage and for incapacitation in miniature pigs. This report presents the dosimetry aspects of that research program.

The objectives of the research reported herein were to characterize the radiation fields and to determine the depth-dose patterns for neutrons and for gamma rays across the intestinal and brain regions of pig cadavers.

## II. MATERIALS AND METHODS

### Experimental criteria

As neutrons may give substantial contributions to dose in the initial radiation phase from nuclear weapons, it was deemed necessary to determine the relative effectiveness of two significantly different incident radiations to biological end points. Consequently, the criteria for the shields to modify the reactor leakage spectra were specified for a free-in-air exposure condition. Neutron to gamma ray and gamma ray to neutron tissue kerma ratios, free-in-air, of the order of 15 were desired.

The interpretation of the radiobiological experiments performed required knowledge of the total absorbed dose pattern for the two significantly different incident radiation fields in order to classify the irradiation in accordance with the system of the International Commission on Radiological Units and Measurements (ICRU).<sup>5</sup> For the intestinal damage portion of the study a midintestine tissue dose rate of 500 rads/minute was specified. In addition, the animals were to be rotated 180 degrees at the midpoint of the irradiation to provide a bilateral and more nearly uniform exposure.

For the incapacitation portion of the study a unilateral type irradiation was specified. The midbrain location was the point of normalization to correlate biological end points. A midbrain tissue dose rate of 2000 rads/minute was specified.

### Radiation detectors

Neutron spectra. Detectors sensitive to neutrons only above a certain energy level are referred to as threshold detectors. The fission foil threshold detector system, first proposed by Hurst et al,<sup>3</sup> was used in this study to evaluate changes in neutron spectrum resulting from the presence of shielding materials. The AFRRRI threshold detector system is described in AFRRRI SR66-3.<sup>2</sup>

Neutron and gamma ray tissue kerma, free-in-air. At AFRRRI, the paired chamber concept has been employed for measuring the separate neutron and gamma components of the mixed field emanating from the AFRRRI-TRIGA reactor. To date, this technique has been limited to free-field measurements employing 50 cm<sup>3</sup> spherical ionization chambers.

The first of the two ion chambers is fabricated from tissue-equivalent plastic and is filled with tissue-equivalent gas. The plastic is a Shonka A-150 mixture and contains C<sub>6.456</sub>, H<sub>10.2</sub>, N<sub>0.25</sub>, O<sub>0.25</sub>, F<sub>0.1287</sub> and Ca<sub>0.0635</sub>.<sup>8</sup> The tissue-equivalent filling gas is a mixture of methane 62.6 percent, carbon dioxide 33.8 percent and nitrogen 3.6 percent (percentages are in terms of partial pressure).

The second of the paired chambers is fabricated from graphite and is filled with CO<sub>2</sub> gas. A 50 cm<sup>3</sup> ionization chamber is illustrated in Figure 1.

Depth-dose dosimetry. Measurements of the total tissue kerma for this study were performed using the miniature (0.05 cm<sup>3</sup>) ionization chamber. Designed by

Wyckoff and Shonka, this chamber approximates the composition of tissue, has a large range of sensitivity for saturated response, and its measurements are reproducible within  $\pm 3$  percent. AFRRI TN68-9<sup>6</sup> describes the construction and performance of a similar but shorter chamber; Figure 2 is a cross-sectional view.

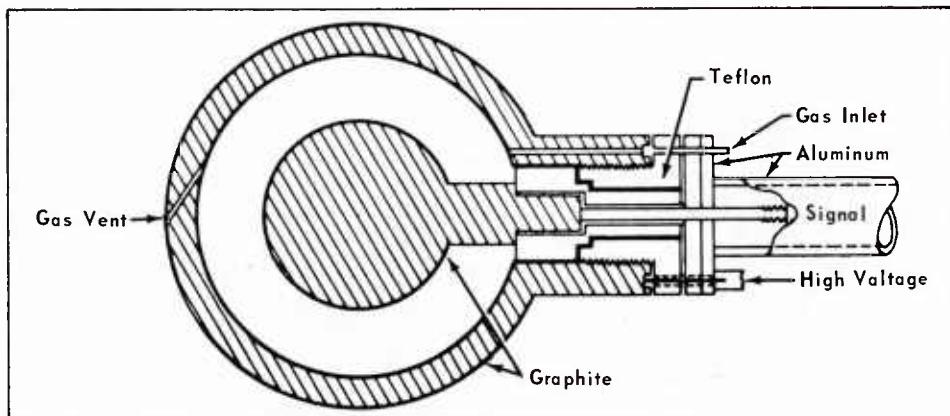


Figure 1. 50 cm<sup>3</sup> carbon-CO<sub>2</sub> ionization chamber

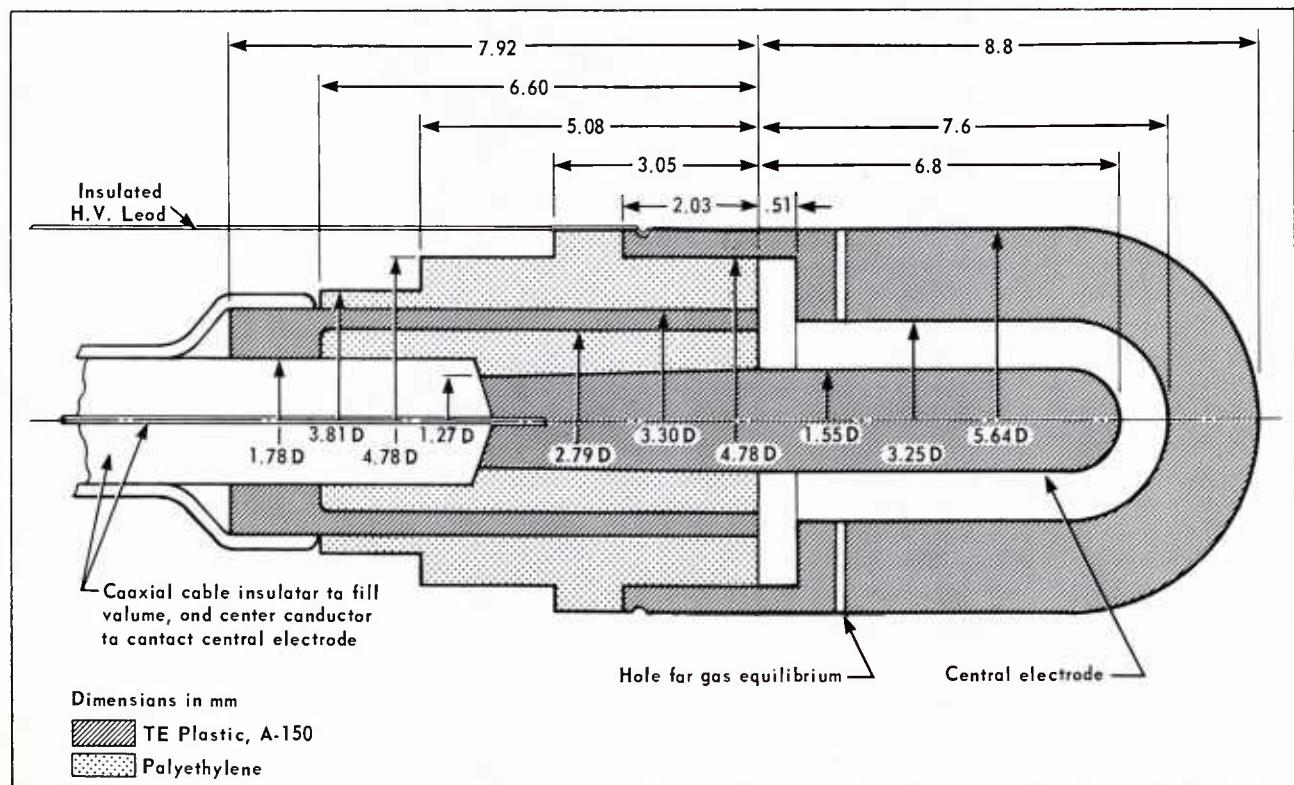


Figure 2. Miniature tissue-equivalent ionization chamber

## Irradiation conditions

AFRRI-TRIGA Exposure Room No. 1. The larger of the two AFRRI-TRIGA reactor exposure rooms is 20 ft x 20 ft x 10 ft high. When positioned adjacent to this exposure room, the TRIGA core is partially unreflected and serves as the radiation source (Figure 3).

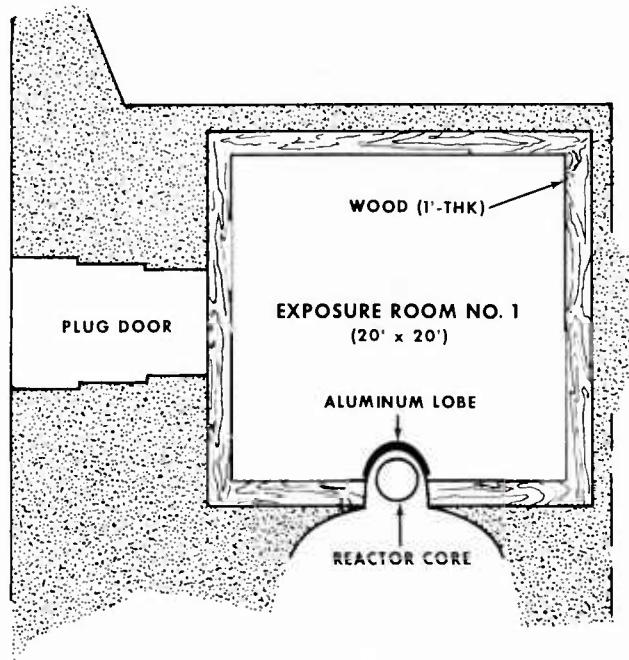


Figure 3. AFRRI-TRIGA Exposure Room No. 1 plan view

To reduce the production of  $^{41}\text{Ar}$  in the exposure room the wood-lined room was modified to minimize the thermal neutron flux density in the exposure volume. The walls and ceiling of Exposure Room No. 1 were resurfaced using Masonite panels covered with a specially developed paint containing  $\text{Gd}_2\text{O}_3$  as the pigment. In addition, a 16-mil aluminum sheet was sprayed with the gadolinium paint (average thickness of the gadolinium was  $22 \text{ mg/cm}^2$ ) and wrapped around the reactor tank protrusion into

the exposure room. A 40-mil cadmium shield was then placed over the gadolinium-coated aluminum primarily to absorb beta radiation generated in the gadolinium.

Enhancement of neutron field. The final design of the portable shield consisted of 6 inches of lead shielding in a 3 ft x 3 ft plane. When in position adjacent to the reactor tank protrusion in the exposure room, the tank and shield were straddled with boron and lead impregnated Masonite to minimize the neutron and gamma ray scatter component into the exposure volume. The shield thickness was assembled in 2-inch increments (up to the total of 6 inches) to permit evaluation of the modified fields and to optimize the final shield design. Figure 4 depicts the exposure array employing the 6-inch lead shield for the incapacitation portion of this study.

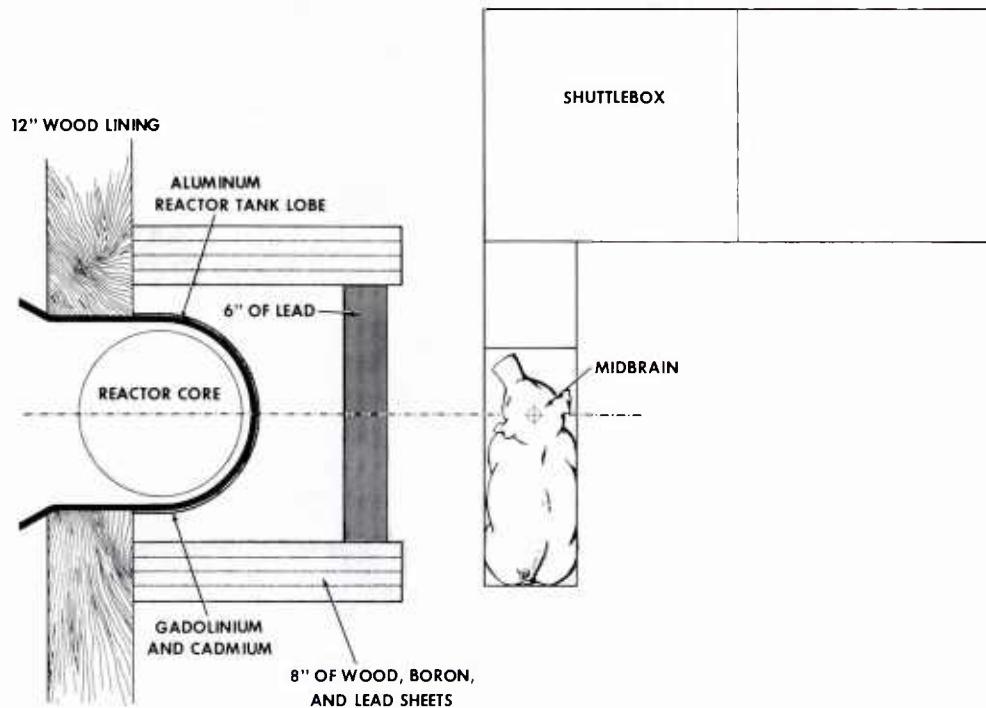


Figure 4. Exposure array for the neutron field

Enhancement of gamma ray field. Neutron contribution to the field was markedly reduced by positioning the reactor core at a distance of 5 inches from the exposure room. The neutron component of the field was thus minimized by thermalization in the water between the core and the exposure room and by capture in the gadolinium-cadmium shield.

### III. RADIATION FIELD MEASUREMENTS

Neutron spectra. The neutron spectra were measured with threshold foils to permit evaluation of the response of the ion chambers in the mixed radiation fields. The average neutron distribution for the modified radiation fields is compared with the normal AFRRRI-TRIGA reactor leakage spectrum in Table I. This table gives the relative probability distribution function of the flux density,  $N(E)$ , as a function of neutron energy. That is, the fraction of the total flux between 1.5 and 3.0 MeV is:

$$\int_{1.5}^{3.0} N(E) dE$$

In determining the relative flux density above 3 MeV, it is assumed that there are no neutrons above 10 MeV. The marked effect of the lead shielding on the neutron

Table I. Relative Neutron Flux Density Distribution

Energy range (MeV)	Relative neutron flux density		
	Normal AFRRRI-TRIGA environment	Enhanced neutron field	Enhanced gamma ray field
0.01 - 0.6	.59	.59	.59
0.6 - 1.5	.27	.31	.22
1.5 - 3.0	.12	.09	.16
3.0 - 10.0	.02	.01	.03

spectrum is to degrade the flux density detected by the sulfur ( $E > 3$  MeV). In the case of the water shield, the relative neutron spectrum is hardened slightly. There are many sources of error involved in evaluating neutron spectra by the threshold foil technique. The most significant errors are from cross-sectional data and foil calibrations. Approximation of the neutron spectra is estimated to be no better than  $\pm 10$  percent.

Tissue kerma rates, free-in-air. Extensive measurements of the components of the exposure environments were performed employing paired  $50\text{ cm}^3$  ionization chambers. There are large uncertainties in the gamma ray component behind the lead and water shields due to the uncertainty in the absolute value of the neutron fluence to kerma factor (k factor) for the carbon- $\text{CO}_2$  chamber. Experimental and computed maximum values of k for a Teflon- $\text{CO}_2$  chamber are given in ICRU Report 10b.<sup>4</sup> As recorded in Report 10b, the maximum value of k has been observed to vary from approximately 0.08 for a neutron energy of 0.5 MeV to 0.24 for a neutron energy of 8 MeV. An evaluation of the AFRRRI-TRIGA reactor spectrum (as determined by threshold foil detectors) was performed by Sayeg and yielded 0.12 as a best estimate of k.<sup>7</sup> Fluence to kerma conversion factors for carbon were calculated from data by Bach and Caswell.<sup>1</sup> For a carbon- $\text{CO}_2$  chamber these calculations yield a best estimate of  $k = 0.11$  behind the lead shield, and  $k = 0.12$  for the water shield. Assigning these values to the response of the carbon- $\text{CO}_2$  chamber, the separate neutron and gamma ray dose components, free-in-air, can be computed for the various shielding configurations.

It can be shown that a  $\pm 10$  percent uncertainty in the neutron fluence to kerma factor for the carbon chamber behind the lead shield can introduce a maximum error of less than 3 percent in the neutron kerma regardless of the neutron to gamma ray kerma ratio. The error in the number quoted for the gamma dose can be as high as  $\pm 25$  percent when the gamma rays contribute less than 10 percent to the total dose. Figures 5 and 6 summarize the free-in-air unperturbed environment for the two different radiation fields as a function of distance from the center line of the reactor core. The error limits illustrated in Figure 5 are associated with a  $\pm 10$  percent uncertainty in the absolute value of the  $k$  factor for the carbon chamber. Superimposed on the data curves is the exponential  $d^{-2}$ .

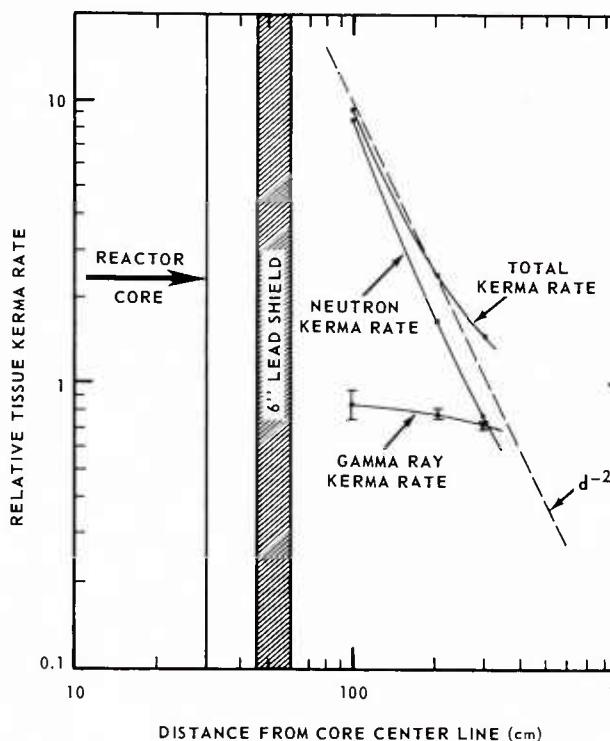


Figure 5. Tissue kerma rates for enhanced neutron field

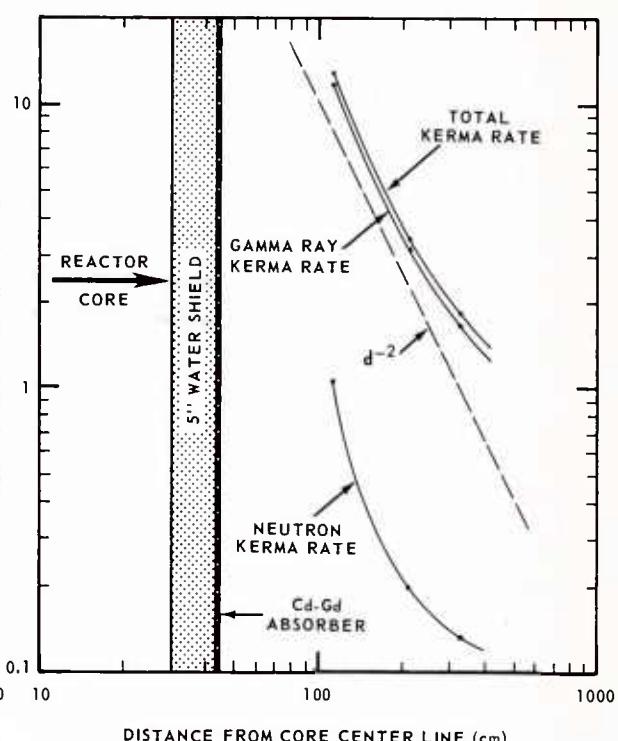


Figure 6. Tissue kerma rates for enhanced gamma ray field

#### IV. DEPTH-DOSE DISTRIBUTIONS

Specially prepared pig cadavers were instrumented with miniature tissue-equivalent ionization chambers (Figure 7) to characterize the irradiations and to compare the depth-dose patterns for the two different radiation fields. The instrumented cadavers were irradiated in the same Lucite cages employed in subsequent biological experiments. All irradiations for dosimetry measurements were performed unilaterally at a total dose rate, free-in-air, of 500 rads per minute.

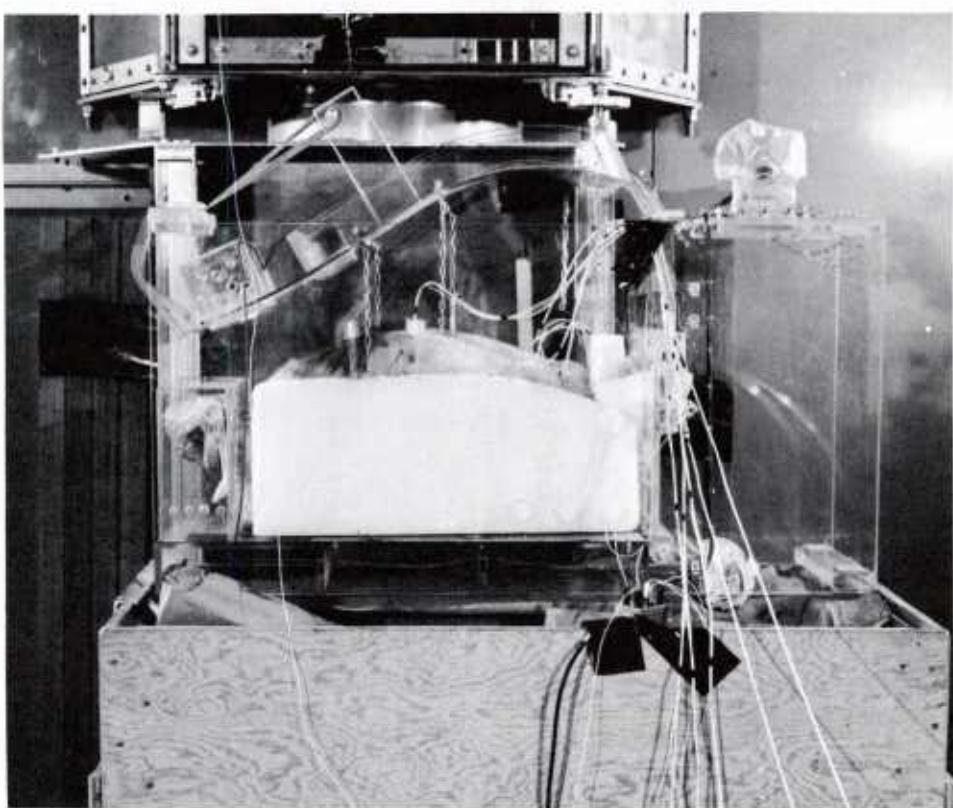


Figure 7. Typical dosimetry array in pig cadaver

For this study, depth-dose measurements were limited to the use of the  $0.05\text{ cm}^3$  tissue-equivalent ionization chamber to determine the total dose distribution for the two significantly different incident radiation fields. Measurements are presently

underway to employ the paired miniature chambers for resolution of radiation components within the specimens. These data will be reported at a later date.

Depth-dose distribution through intestinal region. Within the intestinal region, probes were located at 15 cm in depth and their location was verified by a dissection of the specimen. For the high neutron to gamma ray field, two depth-dose patterns were measured, an anterior and a posterior profile. The specimen was positioned with the midintestine location at 104 cm from the center line of the reactor core. At this location, the incident neutron to gamma ray ratio was 10. Figure 8 illustrates the depth-dose patterns for the two profiles. The dissection of the specimen revealed that the ion chamber position in the middle of the anterior profile was behind the spleen, pancreas, stomach and spiral colon. Such a position would account for the slight depression in the anterior pattern.

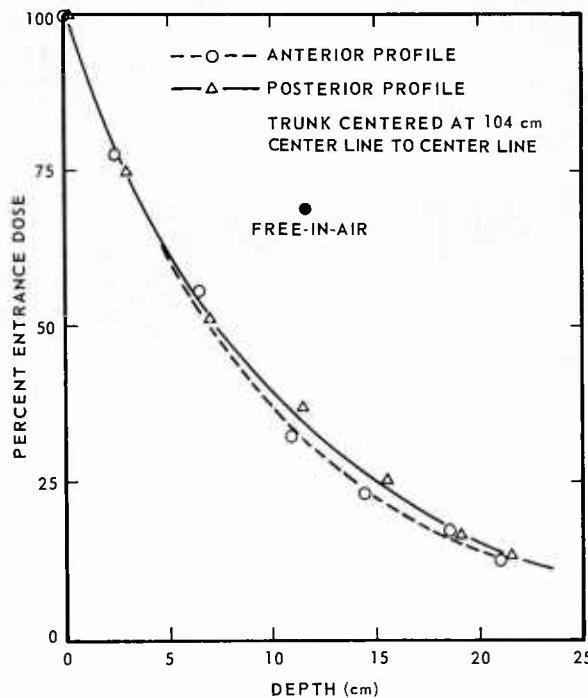


Figure 8. Depth-dose distribution (swine trunk)

Since the prime experimental criterion for this portion of the neutron effectiveness study was to approach a Class A type irradiation, the specimen was relocated to 150 cm from the center line of the reactor to flatten the depth-dose distribution through the intestinal region. At this location the incident neutron to gamma ray ratio was 5. In this configuration, only the posterior depth-dose pattern was measured. Figure 9 compares the patterns for the two specimen locations. At the 150 cm position, a vertical dose pattern was measured through the center probe from 5 cm to 17.5 cm in depth. The results indicated a maximum to minimum ratio of 1.1. Measurements of the lengthwise dose distribution across the intestinal region are summarized in Table II. For purposes of an intestinal damage study, a Class A exposure is approached at the 150 cm position only if one assumes that the outer 4 cm of the body wall is of no interest to the study and the specimen is rotated about the spiral colon.

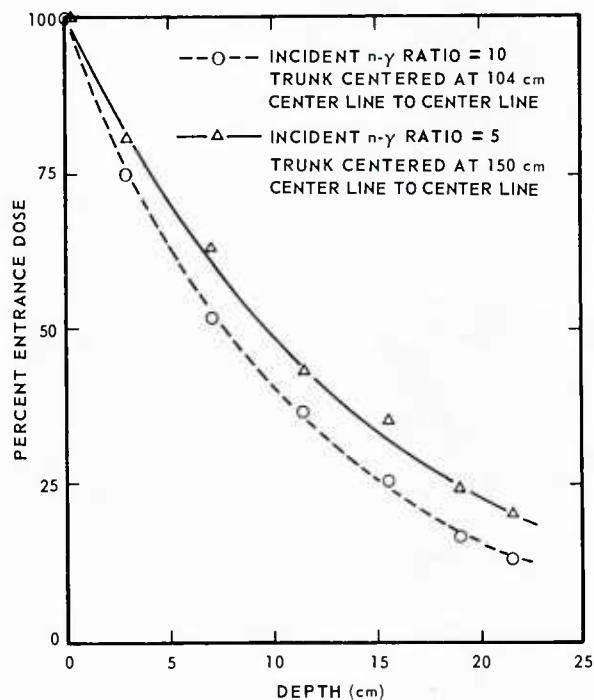


Figure 9. Depth-dose distribution (swine trunk)

Table II. Lengthwise Dose Distribution in Swine Trunk (150 cm center line to center line)

Probe location	Relative kerma
Distal colon	.87
Posterior of intestine	.98
Spiral colon	1.00
Anterior of intestine	.95

It is noted that there are locations within the intestinal region (such as the distal colon) where the depression in the dose renders the irradiation condition as Class B.

A second specimen was instrumented to determine the depth-dose profile for the high gamma ray portion of the study. The probes in this specimen were positioned at 15 cm in depth through the center of the intestinal region. The center line of the intestine was positioned as closely as possible to the reactor tank lobe while maintaining the capability for rotating the specimen midway through the irradiation. At this location, the middle of the intestine was 112.7 cm from the center line of the reactor core. A comparison of the depth dose for the high gamma ray (112.7 cm center line to center line) and the high neutron (150 cm center line to center line) fields is depicted in Figure 10. Data of the depth-dose distribution for this specimen in the high neutron field were compared with data depicted in Figure 9. No significant difference was discernible. A comparison of the lengthwise distribution for both the high neutron and high gamma ray fields is illustrated in Figure 11.

Depth-dose distribution through the brain region. Depth-dose patterns across the brain region were obtained for the two radiation fields described in Section III. For the high neutron field the midbrain probe was located at 104 cm from the center line of the reactor core. This location was predicated upon the overriding requirement for a midbrain kerma rate of 2000 rads/minute and resulted in an incident free-in-air ratio of neutron dose to gamma dose of 10. For the case of the high gamma field, the midhead location was 72.7 cm from the core center line; this position was the closest to the exposure room lobe physically possible. Measurements of the depth dose across the brain for the two fields are summarized in Figure 12. These data as well as their relationship to the midthorax dose are tabulated in Table III.

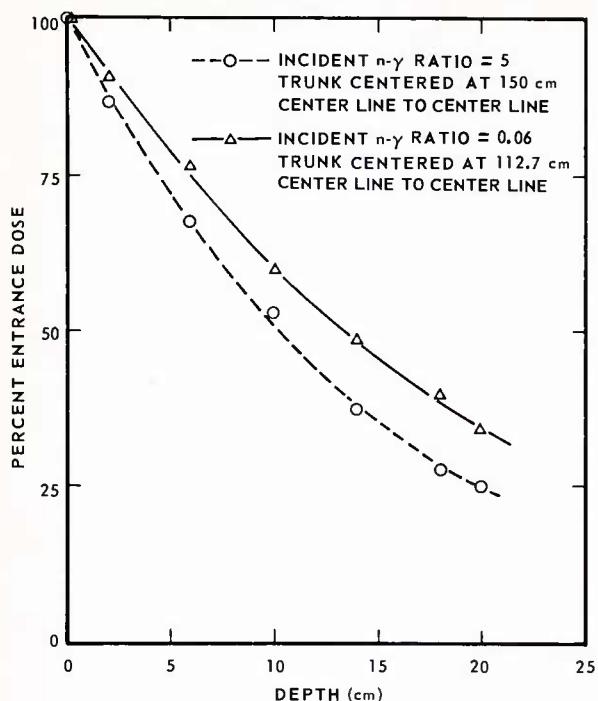


Figure 10. Depth-dose distribution (swine trunk)

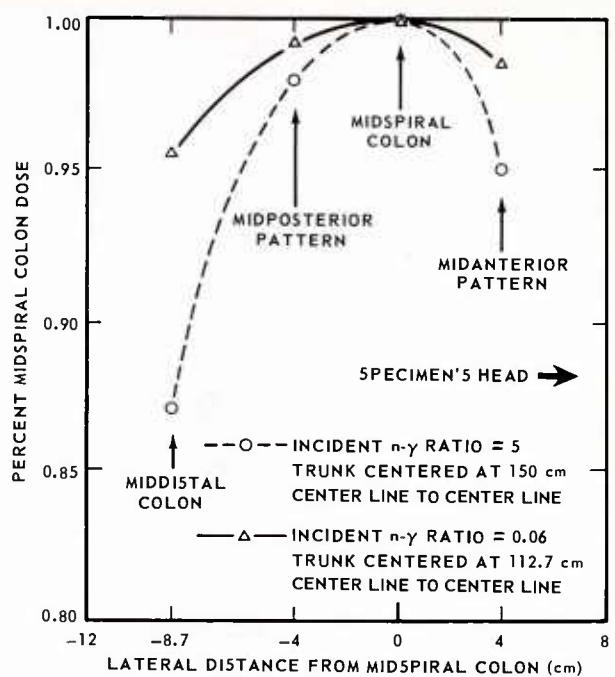


Figure 11. Lateral-dose distribution (swine trunk)

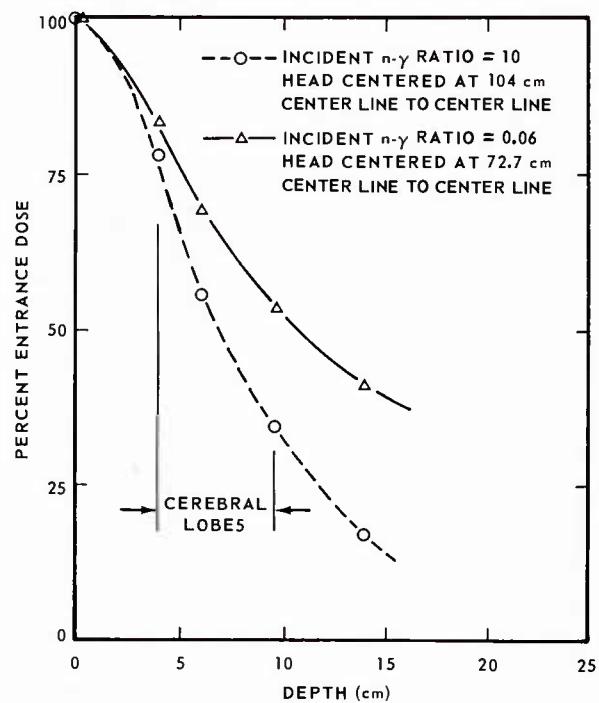


Figure 12. Depth-dose distribution (swine head)

Table III. Depth-Dose Profile across the Brain  
of a Miniature Pig

Probe location	Percent of midbrain kerma	
	High neutron field	High gamma field
Head entrance	180	145
Brain entrance	140	120
Midbrain	100	100
Brain exit	63	78
Head exit	31	60
Midthorax	62	74

From the above it is clearly evident that the irradiations for the incapacitation portion of the study are Class B, nonuniform irradiations. In addition it is noted that the head entrance to exit ratio is greater than 5 for the neutron field and less than 2.5 for the gamma ray field. Entrance to exit ratios in the brain region are 2.2 and 1.5, respectively, for the neutron and gamma ray fields.

#### V. SUMMARY

The dosimetry methods employed in this study are considered to be among the most reliable for determining free-in-air neutron to gamma ratios and total kerma distributions of a modified mixed field of neutron and gamma radiations such as from the AFRRI-TRIGA reactor. The precision of all depth-dose measurements was within 3 percent whereas the accuracy of the dose measurements is estimated to be  $\pm 10$  percent. The limitation on accuracy is attributed to the use of the paired chamber technique and the knowledge of the neutron spectrum as determined by threshold foils.

The data presented in this report reinforce the determinations and findings of the ICRU as related to the classification of irradiation conditions. The validity of

characterizing irradiations of relatively large specimens by a single dose point, such as midintestine or midhead, is of questionable value. As a minimum, irradiations should be supplemented with at least depth-dose patterns through the region of interest.

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13. ABSTRACT

Miniature pig cadavers were instrumented and irradiated in a neutron field (incident neutron to gamma kerma ratio of 5-10) and a gamma ray field (incident gamma to neutron kerma ratio of 10-15) from the AFRRI-TRIGA reactor. Characterization of the radiation field included free-in-air measurements of the neutron and gamma ray components employing the paired chamber concept. Depth-dose patterns across the brain and intestinal regions were measured for each of the radiation fields employing a miniature tissue-equivalent ionization chamber.